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CALCULATIONS OF ECONOMY OF 18-CYLINDER RADIAL AIRCRAFT ENGINE WITH EXHAUST-GAS TURBINE GEARED TO THE CRANKSHAFT

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SUMMARY

Calculations based on dynamometer test-stand data obtained on an 18-cylinder radial engine were made to determine the improvement in fuel consumption that can be obtained at various altitudes by gearing an exhaust-gas turbine to the engine crank-shaft in order to increase the engine-shaft work.

The calculations indicated that, for turbine and auxiliary supercharger efficiencies of 85 percent, minimum net brake specific fuel consumptions of 0.357 pound per brake horsepower-hour at an altitude of 10,000 feet and of 0.323 pound per brake horsepower-hour at 30,000 feet can be obtained by gearing the exhaust-gas turbine to the engine crankshaft and operating the engine at a speed of 2000 rpm, an inlet-manifold pressure of 40 inches of mercury absolute, and a fuel-air ratio of 0.063.

The reduction in net brake specific fuel consumption that can be obtained if the exhaust-gas turbine supplies all the auxiliary supercharger power and if its residual power is transmitted through gears to the engine crankshaft, as compared with auxiliary turbosupercharging, is approximately 14 percent at an altitude of 10,000 feet and 21 percent at 30,000 feet.

The net brake specific fuel consumption with a geared turbine is a minimum for engine exhaust pressures approximately 25 percent above inlet-manifold pressure and varies only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure.

INTRODUCTION

The use of an exhaust-gas turbine to drive a supercharger at high altitudes is an effective method of maintaining sea-level engine power at altitude. Analysis has shown, however, that the waste energy of exhaust gases is recovered more effectively by maintaining an engine exhaust pressure higher than the minimum required for turbosupercharging and thus increasing the work output of the exhaust-gas turbine. The extra turbine power beyond that required for supercharging can be supplied to the engine crankshaft through suitable gearing (compound operation).

The purpose of the analysis reported is to determine the improvement in net brake specific fuel consumption that can be obtained if an engine is equipped with a geared turbine and supercharger as compared with the engine using a standard turbosupercharger. The calculated values of specific fuel consumption presented for an engine-turbine combination were based on NACA test data obtained on an 18-cylinder

radial engine. Operating conditions for which the brake specific fuel consumption of the combination is a minimum are given. The required turbine-nozzle area is also calculated to indicate the size of turbine suitable for geared operation.

Because the engine, the turbine, and the supercharger have different characteristics, elements designed to give maximum efficiency at some operating conditions are incorrectly matched at other conditions. Provision must therefore be made to obtain satisfactory performance over the entire operating range. The problem of obtaining a wide operating range is briefly discussed.

The investigation reported was conducted at the NACA Cleveland Laboratory in the fall of 1944.

METHODS

This analysis is based on dynamometer test-stand data obtained with an 18-cylinder radial engine operated at various speeds, inlet-manifold pressures, and exhaust pressures. The data were obtained with the carburetor-inlet pressure adjusted by a butterfly valve in the charge-air intake pipe ahead of the engine to provide the desired inlet-manifold pressure with wide-open engine throttle in all runs. Pertinent specifications of the engine are as follows:

Displacement, cubic inches	2804
Compression ratio	6.65
Valve timing:	
Inlet opens, degrees B. T. C.	20
Inlet closes, degrees A. B. C.	76
Exhaust opens, degrees B. B. C.	76
Exhaust closes, degrees A. T. C.	20
Valve overlap, degrees	40
Engine-stage supercharger impeller diameter, inches	11
Engine-stage supercharger gear ratio	7.6:1
Spark advance, degrees B. T. C.	25

The test data and the values of air flow and brake horsepower, corrected to a carburetor-air temperature of 90° F, are shown in table I. Although the carburetor-air temperatures obtained in flight depend upon the amount of auxiliary supercharging and intercooling used, the arbitrary use of a temperature of 90° F for all calculations was considered justified in this analysis because specific fuel consumption is almost independent of carburetor temperature. The engine performance at an engine speed of 2000 rpm and a fuel-air ratio of 0.063 for various engine exhaust pressures, obtained

TABLE I.—SUMMARY OF PERTINENT TEST DATA ON 18-CYLINDER RADIAL AIRCRAFT ENGINE

Run	Engine speed (rpm)	Fuel-air ratio	Carburetor-air pressure (in. Hg absolute)	Carburetor-air temperature (°F)	Inlet-manifold pressure (in. Hg absolute)	Inlet-manifold mixture temperature (°F)	Engine exhaust pressure (in. Hg absolute)	Engine power (bhp)	Exhaust-gas temperature (°F)	Cylinder-head temperature (°F)	Cooling-air pressure drop (in. water)	Cooling-air temperature (°F)	Fuel flow (lb/hr)	Charge-air flow (lb/hr)	Corrected charge-air flow (lb/hr) ¹	Corrected engine power (bhp)
319	1612	0.0683	31.22	92	30.26	120	8.00	1106	1256	331	12.9	110	610	7100	7100	1099.5
320	1602	0.0680	31.20	92	30.20	120	19.00	1080	1227	330	12.1	111	552	6426	6430	1047.7
321	1604	0.0648	31.00	92	30.25	127	22.75	994	1445	332	12.2	114	526	6228	6228	926.6
322	1600	0.0647	31.00	92	30.25	120	37.65	935	1487	337	13.1	114	505	6058	6058	922.8
323	1600	0.0650	31.00	92	30.25	122	47.90	844	1407	341	13.1	115	486	5859	5858	918.8
324	1601	0.0651	30.99	93	30.25	127	56.30	752	1378	341	12.2	115	453	5321	5321	784.5
247	1800	0.0647	29.33	91	40.00	121	8.30	1207	1439	348	13.1	114	554	7723	7723	1207.6
248	1762	0.0642	29.15	91	40.00	122	16.20	1174	1436	351	12.8	114	521	7373	7413	1186.2
249	1801	0.0638	29.15	91	30.25	126	24.00	1125	1480	359	12.8	114	506	7106	7106	1138.4
250	1798	0.0638	29.15	92	30.25	137	32.10	1080	1486	362	13.0	114	502	6937	6934	1061.6
251	1796	0.0648	29.08	92	30.25	140	39.20	1020	1486	354	12.9	114	570	6728	6776	1028.4
252	1794	0.0647	29.15	94	40.00	148	49.15	934	1473	365	12.7	115	543	6412	6456	950.1
220	2006	0.0653	27.50	91	40.25	137	7.96	1272	1483	349	13.9	94	787	5636	5656	1361.2
230	1999	0.0649	27.50	90	40.00	138	16.25	1228	1545	351	13.8	95	707	5330	5354	1334.0
231	1994	0.0655	27.30	90	40.05	138	24.40	1288	1525	352	13.8	95	698	5153	5153	1244.8
232	1995	0.0650	27.28	90	40.05	141	32.20	1223	1533	354	13.9	94	682	5028	5028	1357.8
233	2003	0.0654	27.05	90	40.10	144	39.25	1175	1524	356	14.2	94	656	7760	7605	1178.5
234	1994	0.0654	27.05	90	30.25	147	49.30	1087	1509	359	14.2	94	639	7474	7606	1001.9
313	2202	0.0601	26.00	103	30.25	123	8.92	1413	1516	359	18.2	116	287	9127	9239	1426.7
314	2198	0.0654	26.58	103	40.00	154	19.15	1275	1541	359	18.4	115	701	5906	5918	1361.8
315	2195	0.0658	26.53	104	40.05	155	28.85	1250	1561	362	18.3	115	745	5857	5723	1236.7
316	2207	0.0653	26.61	107	40.05	170	37.65	1262	1545	364	18.4	115	718	5417	5356	1287.9
317	2203	0.0650	26.55	107	40.05	174	45.30	1185	1534	369	18.6	117	686	5068	5128	1168.5
318	2197	0.0658	26.50	108	40.00	178	59.75	1023	1509	378	18.6	117	646	7574	7707	1040.7
325	2405	0.0657	24.20	100	30.25	178	7.89	1477	1567	354	22.2	100	844	9150	9243	1491.2
326	2403	0.0653	24.20	102	40.10	178	16.05	1447	1573	354	22.8	100	826	9038	9157	1450.9
327	2395	0.0656	24.00	103	40.00	178	25.72	1282	1577	354	22.1	100	803	9367	9367	1361.7
328	2398	0.0654	23.98	104	40.00	180	35.65	1209	1565	357	22.2	100	777	9101	9224	1226.0
329	2398	0.0652	23.98	105	40.00	184	45.09	1220	1568	361	22.2	100	745	6784	6801	1234.2
330	2405	0.0653	23.93	107	40.15	188	58.42	1065	1541	366	22.2	100	704	5261	5329	1007.4
122	1992	0.0656	20.70	104	30.03	157	8.30	936	1580	351	9.8	116	518	6018	6148	919.1
123	2000	0.0657	20.62	104	30.05	158	14.95	912	1475	351	9.8	115	513	5973	5987	923.8
124	2001	0.0651	20.58	105	30.13	160	22.45	871	1510	353	9.9	115	500	5807	5871	851.1
125	1996	0.0659	20.53	106	30.15	162	28.70	820	1533	353	9.9	115	485	5648	5725	851.1
126	1994	0.0651	20.48	106	30.05	165	35.03	767	1425	354	9.9	116	457	5423	5530	781.0
127	1999	0.0642	20.33	108	30.05	170	42.53	703	1430	355	9.8	116	456	5230	5306	714.1
11	1997	0.0644	23.35	93	34.00	152	8.70	1023	1427	356	8.8	117	567	6943	6964	1076.2
12	1998	0.0646	23.38	93	34.00	154	16.35	1057	1438	360	8.9	117	571	6784	6841	1065.2
13	1997	0.0643	23.20	94	33.90	158	22.80	1022	1453	368	8.9	117	561	6653	6707	1032.4
14	1994	0.0641	23.25	94	34.00	160	28.85	988	1482	369	8.8	117	548	6434	6541	937.8
15	1992	0.0640	23.10	96	34.00	164	40.20	988	1470	365	8.9	118	517	6156	6218	921.4
293	1997	0.0649	30.06	86	44.95	181	9.30	1579	1518	351	27.8	99	840	9350	9570	1574.2
294	1993	0.0649	30.69	95	44.92	181	18.88	1521	1539	344	27.3	99	818	2601	2613	1459.2
295	1995	0.0653	30.51	95	45.00	183	30.75	1457	1538	350	27.6	99	798	9274	9263	1454.5
296	1996	0.0659	30.78	95	45.03	185	46.95	1584	1598	349	27.1	99	775	9022	9026	1374.2
297	2004	0.0652	30.03	97	45.05	180	52.20	1578	1508	351	27.0	100	728	5518	5606	1294.1
298	2004	0.0648	30.35	99	44.97	146	63.95	1145	1510	359	27.8	100	651	5038	5017	1112.6
299	2001	0.0604	27.80	91	40.00	148	8.12	1381	1640	354	24.7	104	533	8478	8511	1391.2
300	2000	0.0601	27.49	92	39.98	150	18.48	1299	1630	356	24.6	105	5201	8278	8310	1310.7
355	1998	0.0629	27.35	93	40.05	152	28.65	1245	1629	360	24.5	104	555	8006	8010	1255.0
366	2001	0.0601	27.80	93	40.01	155	38.90	1655	1608	368	24.7	104	529	7654	7669	1107.6
490	2005	0.0630	26.19	90	38.00	151	7.80	1233	1623	351	22.0	103	504	7999	7979	1200.8
491	1994	0.0631	26.12	90	37.95	153	19.92	1168	1700	348	24.2	103	436	7708	7741	1175.1
492	2009	0.0631	26.92	91	38.08	156	30.09	1128	1702	348	24.7	110	476	7638	7195	1114.0
493	1996	0.0626	26.90	92	37.95	159	39.98	1204	1688	358	24.2	110	446	7194	7210	1039.9
494	2011	0.0630	26.79	91	38.00	154	48.50	987	1661	374	24.6	111	438	6941	6981	1031.8

¹ Corrected to carburetor-air temperature of 90° F and for variations of engine speed and manifold pressure from nominal.

TABLE II.—ESTIMATED PERFORMANCE OF 18-CYLINDER RADIAL AIRCRAFT ENGINE

[Engine speed, 2000 rpm; inlet-manifold pressure, 40 in. Hg absolute; fuel-air ratio, 0.063; carburetor-air temperature, 60° F; carburetor-air pressure, 27.35 in. Hg absolute]

Engine exhaust pressure (in. Hg absolute)	Engine power (bhp)	Exhaust temperature (°F)	Charge-air flow (lb/hr)
10	1202	1694	8428
20	1260	1724	8247
30	1301	1724	8000
40	1127	1708	7710
50	1043	1677	7386
60	982	1645	7034

For the computation of net brake horsepower of the combination, the auxiliary supercharger and the turbine were assumed to be on the same shaft and the difference between their powers to be transmitted through gears to the engine crankshaft. The exhaust-gas temperatures used in computing turbine power are included in tables I and II. The temperatures in table I were measured approximately 1 1/4 feet downstream of the junction of the two halves of the exhaust manifold. The calculated turbine work is that resulting from expansion of the entire engine exhaust-gas flow from engine exhaust static pressure to the altitude atmospheric pressure. The calculated auxiliary supercharger power is that required to compress the engine combustion-air flow from the altitude atmospheric static pressure to the engine carburetor pressure. All supercharger computations pre-

sented relate to the auxiliary supercharger because the power of the engine-stage supercharger is contained in the measured engine power listed in the tables of data. Supercharger and turbine efficiencies of 85 percent were used in most of the computations. In addition, some computations were made with efficiencies of 70 percent in order to show the effect of supercharger and turbine efficiencies on performance of the combination. A gear efficiency of 95 percent was used for the calculations. The net power, when the turbine power is greater than the supercharger power, therefore is:

$$\text{engine power} + 0.95 \\ (\text{turbine power} - \text{auxiliary supercharger power})$$

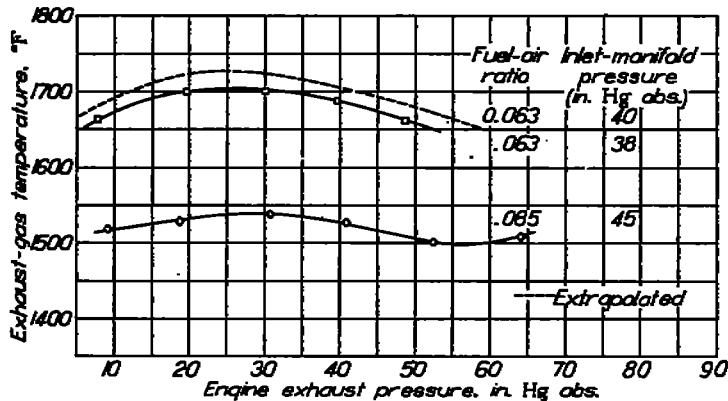


FIGURE 1.—Variation of exhaust-gas temperature with engine exhaust pressure at two fuel-air ratios and three inlet-manifold pressures. 18-cylinder radial aircraft engine; engine speed, 2000 rpm.

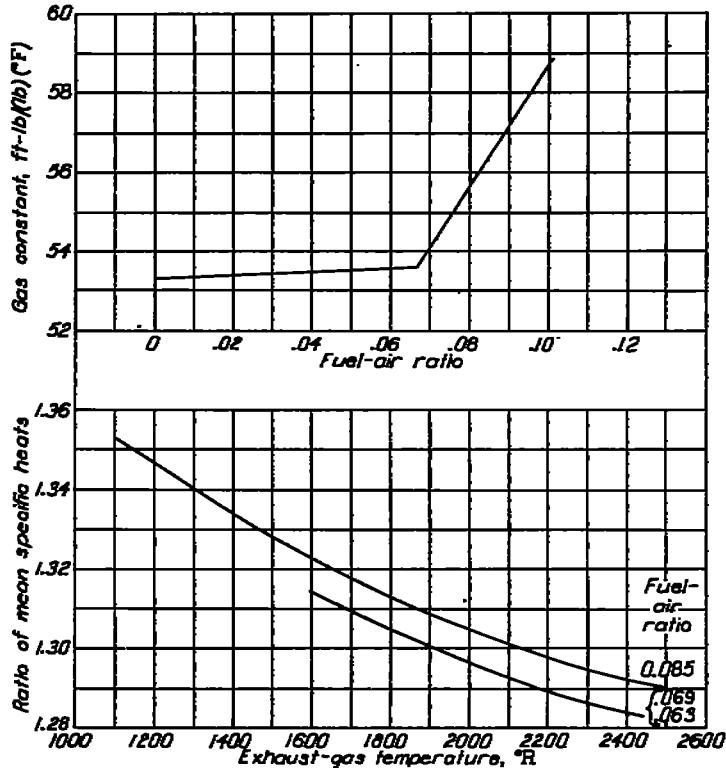


FIGURE 2.—Variation of gas constant with fuel-air ratio and variation of ratio of mean specific heats with exhaust-gas temperature. Hydrogen-carbon ratio, 0.178. (Data from reference 1.)

The fuel flow was divided by the net power to give a net brake specific fuel consumption for the combination.

At each condition computed, the supercharger and the turbine were assumed to be matched to the engine for operation with engine throttle full open and turbine waste gate closed.

DISCUSSION OF CURVES

The variation of exhaust-gas temperature with engine exhaust pressure at two fuel-air ratios and three inlet-manifold pressures at an engine speed of 2000 rpm is presented in figure 1.

Variation of the gas constant for exhaust gas with fuel-air ratio and the variation of the ratio of mean specific heats with exhaust-gas temperature for three fuel-air ratios were taken from reference 1 and plotted in figure 2. These values were

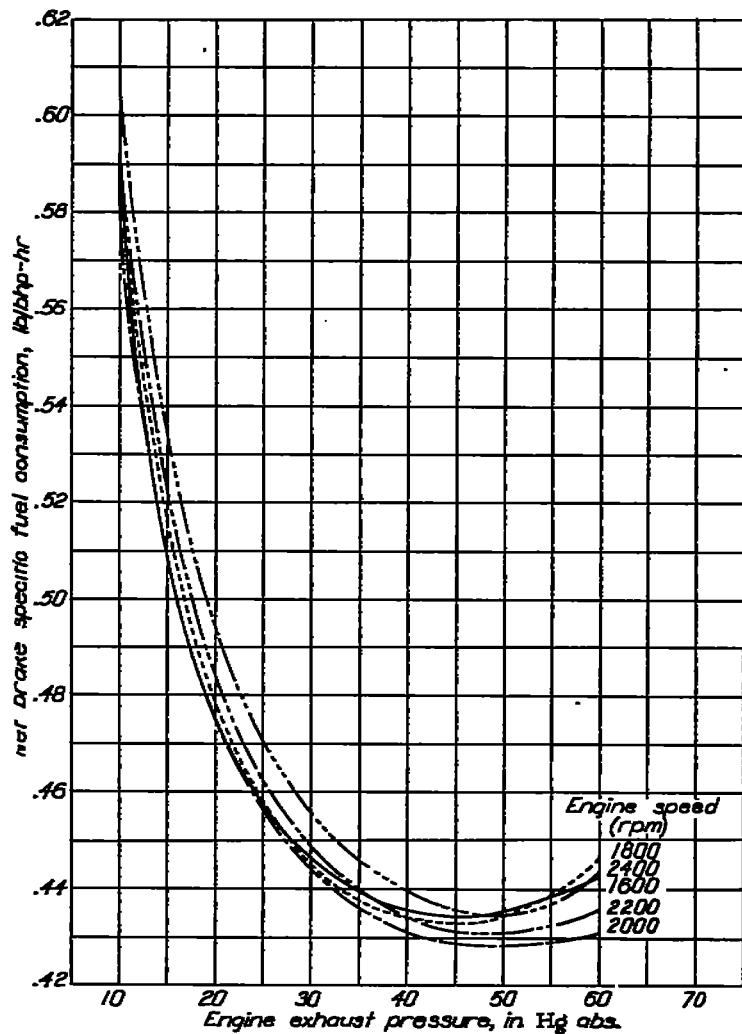


FIGURE 3.—Variation of net brake specific fuel consumption with engine exhaust pressure at various engine speeds. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.068; inlet-manifold pressure, 40 inches of mercury absolute; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

used in the equations of reference 1 to compute the turbine power. The values of the ratio of mean specific heats are accurate for expansion from the exhaust-gas temperatures through a pressure ratio of 3, and a negligible error is introduced in the range of pressure ratios considered.

The net brake specific fuel consumption of the engine-turbine-supercharger combination at various engine speeds for a fuel-air ratio of 0.085, an inlet-manifold pressure of 40 inches of mercury absolute, and an altitude of 30,000 feet is given in figure 3. This figure indicates that minimum specific fuel consumption can be obtained at a speed of approximately 2000 rpm. Because it is reasonable to expect that this speed will also give minimum specific fuel consumption for fuel-air ratios less than 0.085, all subsequent curves are plotted for a speed of 2000 rpm.

The variation in net brake specific fuel consumption of the combination with engine exhaust pressure at an engine speed of 2000 rpm, an altitude of 30,000 feet, and at various inlet-manifold pressures and fuel-air ratios is shown in figure 4. For a fuel-air ratio of 0.085, the minimum net brake

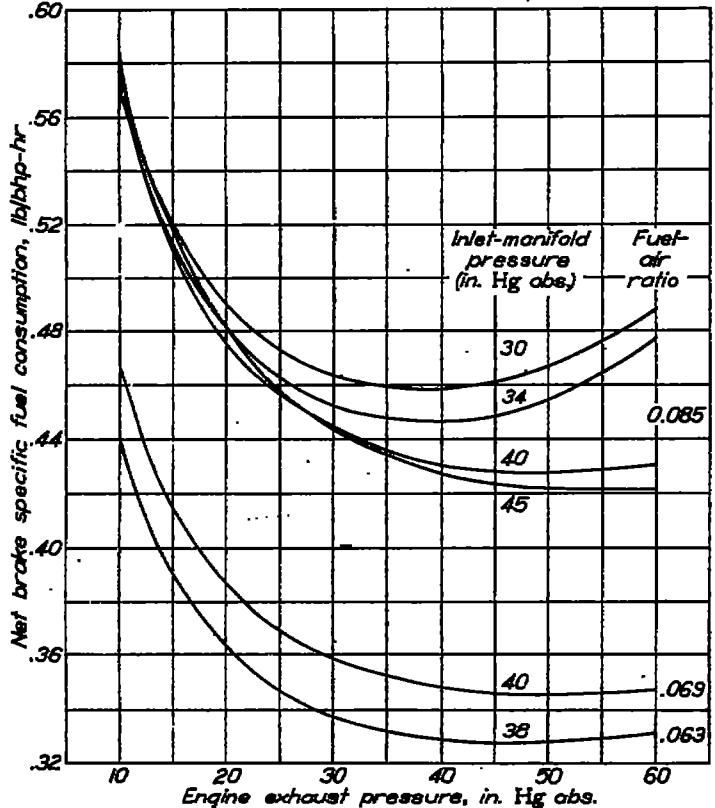


FIGURE 4.—Variation of net brake specific fuel consumption with engine exhaust pressure at various inlet-manifold pressures and fuel-air ratios. 18-cylinder radial aircraft engine with geared turbine and supercharger; engine speed, 2000 rpm; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 98 percent.

specific fuel consumption decreases as inlet-manifold pressure is increased; a large drop in net brake specific fuel consumption also occurs when the fuel-air ratio is decreased from 0.085 to 0.063. The effect of reducing fuel-air ratio is much

greater than that of increasing inlet-manifold pressure. It may be concluded that the most efficient operation occurs at a fuel-air ratio of approximately 0.063 and at the highest inlet-manifold pressure permissible from considerations of engine knock and cooling. At a fuel-air ratio of 0.063 and an engine speed of 2000 rpm, using AN-F-28, Amendment 2, fuel, incipient knock occurred during tests at an inlet-manifold pressure of 39 inches of mercury absolute and an engine exhaust pressure of 28 inches of mercury absolute. The knock became progressively worse as exhaust pressure was increased. The runs at this fuel-air ratio were therefore limited to an inlet-manifold pressure of 38 inches of mercury absolute. Figure 5 presents curves of net brake horsepower of the combination that correspond to the specific-fuel-consumption curves of figure 4.

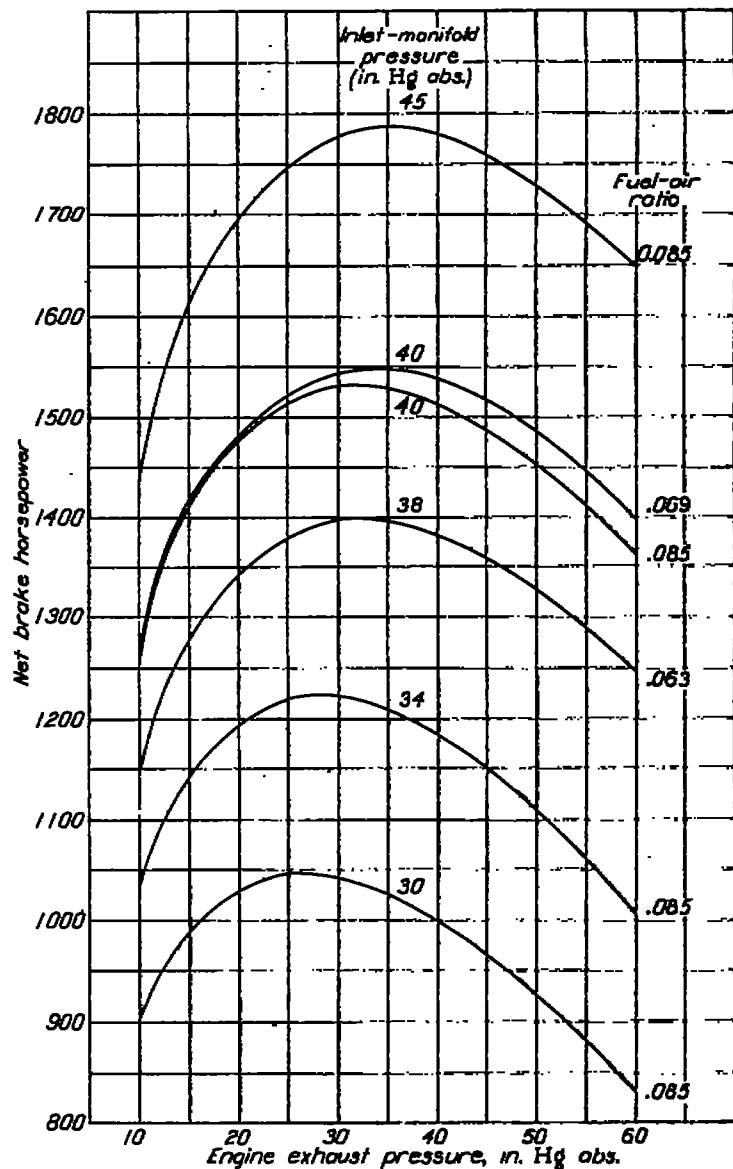


FIGURE 5.—Variation of net brake horsepower with engine exhaust pressure at various inlet-manifold pressures and fuel-air ratios. 18-cylinder radial aircraft engine with geared turbine and supercharger; engine speed, 2000 rpm; altitude, 30,000 feet; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 98 percent.

Net brake horsepower and net brake specific fuel consumption are shown in figure 6 for an engine speed of

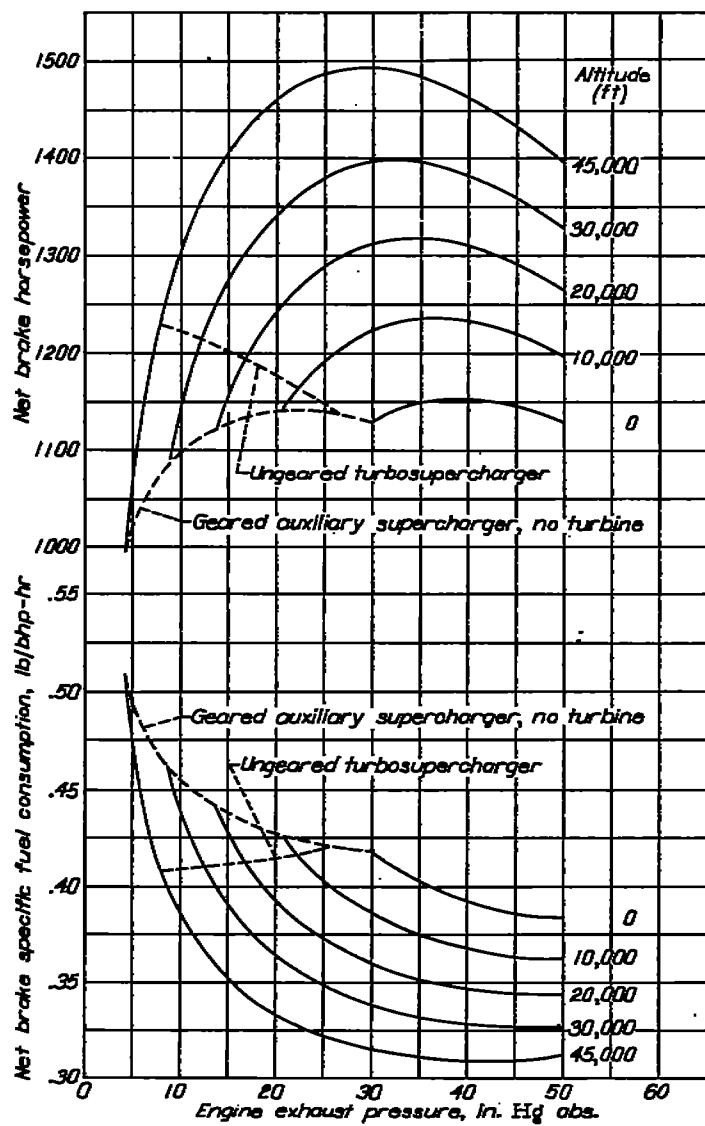


FIGURE 6.—Variation of net brake horsepower and brake specific fuel consumption with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 38 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 88 percent; gear efficiency, 95 percent.

2000 rpm, an inlet-manifold pressure of 38 inches of mercury absolute, and a fuel-air ratio of 0.063 at various altitudes and engine exhaust pressures. Similar curves were calculated assuming a fuel having a higher knock rating than AN-F-28 in the lean range for an inlet-manifold pressure of 40 inches of mercury absolute, based on the extrapolated performance given in table II (fig. 7). In figure 7, maximum net power at an altitude of 30,000 feet occurs at an engine exhaust pressure of approximately 33 inches of mercury absolute. Minimum net brake specific fuel consumption at an altitude of 30,000 feet occurs at an engine exhaust pressure of approximately 50 inches of mercury absolute. There is a trend toward lower optimum engine exhaust pressure at

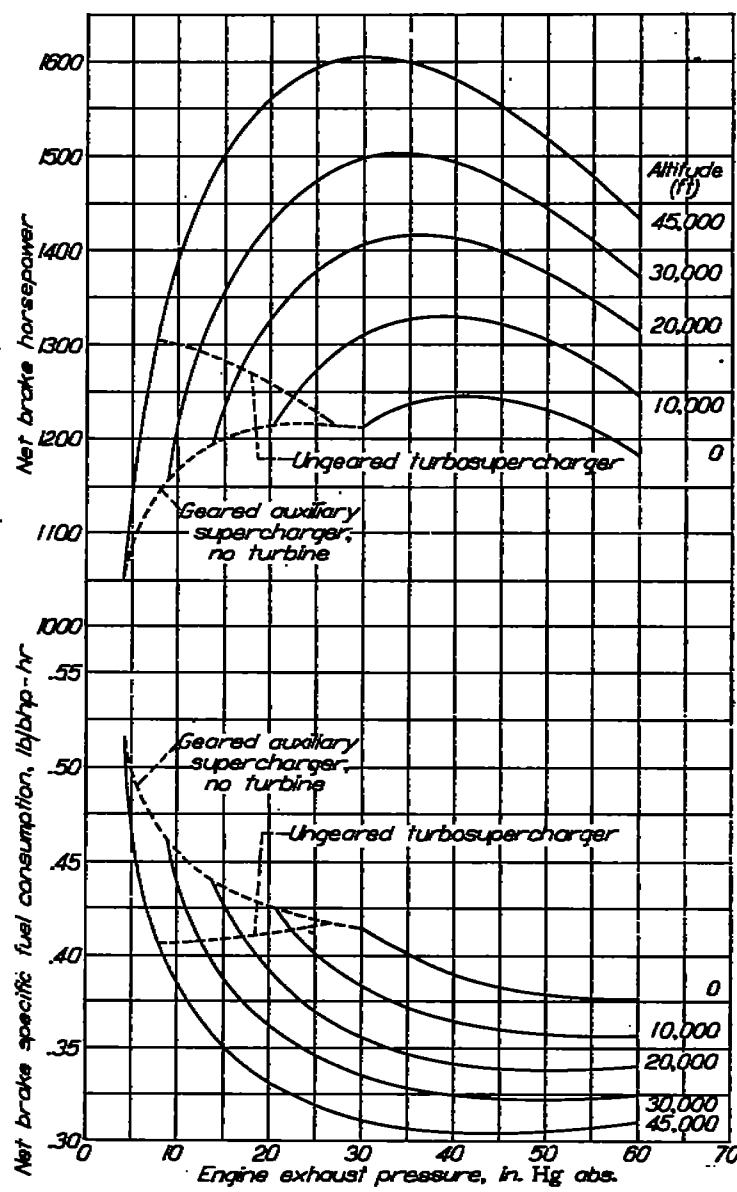


FIGURE 7.—Variation of net brake horsepower and brake specific fuel consumption with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 88 percent; gear efficiency, 95 percent.

higher altitudes, but the curves are flat and little change in net brake specific fuel consumption occurs between engine exhaust pressures of 42 and 60 inches of mercury absolute. In general, net brake specific fuel consumption is a minimum for engine exhaust pressures approximately 25 percent above inlet-manifold pressure and varies only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure. The minimum net brake specific fuel consumptions at 10,000 and 30,000 feet are 0.357 and 0.323 pound per brake horsepower-hour, respectively. If the system is designed to operate at the exhaust pressure for maximum net power, a sacrifice in specific fuel consumption of approximately 3 percent would result.

Table III shows the power produced by the engine and the turbine and the power required for the auxiliary supercharger.

For comparison with the optimum geared-turbine arrangement, cross curves are shown in figures 6 and 7 that represent the following cases:

(a) Engine with geared auxiliary supercharger and no turbine

(b) Engine with ungeared auxiliary turbosupercharger

Current turbosupercharger operation with closed waste gate is approximated by case (b). Figure 7 indicates a reduction in net brake specific fuel consumption of 21 percent at an altitude of 30,000 feet and 14 percent at 10,000 feet with the optimum geared-turbine arrangement, as compared with case (b).

Calculations were also made for case (a) with individual exhaust stacks for auxiliary jet propulsion, assuming the optimum stacks for no engine-power loss, a speed of 350 miles per hour, and a propeller efficiency of 85 percent. The stacks provide an effective increase in engine shaft power of 152 horsepower at 10,000 feet and 203 horsepower at 30,000 feet. The net brake specific fuel consumption is reduced to 0.375 pound per brake horsepower-hour at 10,000 feet and 0.401 pound per brake horsepower-hour at 30,000 feet. The net brake specific fuel consumption obtained for case (a) with individual exhaust stacks for auxiliary jet propulsion was lower than that obtained for the engine with ungeared auxiliary turbosupercharger (case (b)) at 10,000 feet, equal at 30,000 feet, but higher than that obtained with compound operation at both altitudes.

TABLE III.—ENGINE, TURBINE, AND AUXILIARY SUPERCHARGER POWERS

[Engine speed, 2000 rpm; inlet-manifold pressure, 40 in. Hg abs.; fuel-air ratio, 0.063]

Engine exhaust pressure (in. Hg abs.)	Engine power (bhp)	Turbine power, 85 percent efficiency (bhp)	Auxiliary supercharger power, 85 percent efficiency (bhp)	Excess turbine power, 95 percent gear efficiency (bhp)	Net power (bhp)	Turbine power, 70 percent efficiency (bhp)	Auxiliary supercharger power, 70 percent efficiency (bhp)	Excess turbine power, 85 percent gear efficiency (bhp)	Net power (bhp)
Altitude, 10,000 feet									
20.55	1257	0	37	-39	1218	0	45	-53	1204
30.00	1201	114	36	112	1213	127	44	71	1272
40.00	1127	252	35	206	1233	207	42	140	1267
50.00	1043	311	33	263	1206	256	41	153	1226
60.00	952	344	32	297	1240	233	39	207	1193
Altitude, 20,000 feet									
18.75	1280	0	90	-95	1194	0	109	-123	1161
20.00	1260	125	89	86	1223	130	108	19	1279
30.00	1201	306	86	208	1206	263	105	125	1326
40.00	1127	358	83	299	1116	319	101	135	1312
50.00	1043	433	79	336	1270	356	97	230	1263
60.00	952	463	76	356	1211	373	92	239	1191
Altitude, 30,000 feet									
8.88	1206	0	146	-154	1152	0	177	-203	1097
10.00	1203	52	145	99	1203	45	177	-155	1144
20.00	1260	237	143	176	1438	260	174	81	1341
30.00	1201	455	138	301	1502	376	168	176	1377
40.00	1127	521	133	368	1496	420	162	227	1354
50.00	1043	553	128	404	1447	455	158	265	1296
60.00	952	553	122	418	1270	463	143	268	1220
Altitude, 45,000 feet									
4.36	1219	0	255	-269	1080	0	210	-365	854
10.00	1202	336	253	79	1281	277	207	35	1237
20.00	1260	508	247	304	1264	457	300	142	1402
30.00	1201	668	240	437	1608	550	291	280	1421
40.00	1127	711	231	456	1553	585	281	250	1336
50.00	1043	724	231	478	1221	596	269	278	1231
60.00	952	715	211	479	1421	589	256	253	1235

The effect on net brake specific fuel consumption of decreasing the supercharger and turbine efficiencies from 85 to 70 percent and the gear efficiency from 95 to 85 percent is presented in figure 8. These calculations were made for an

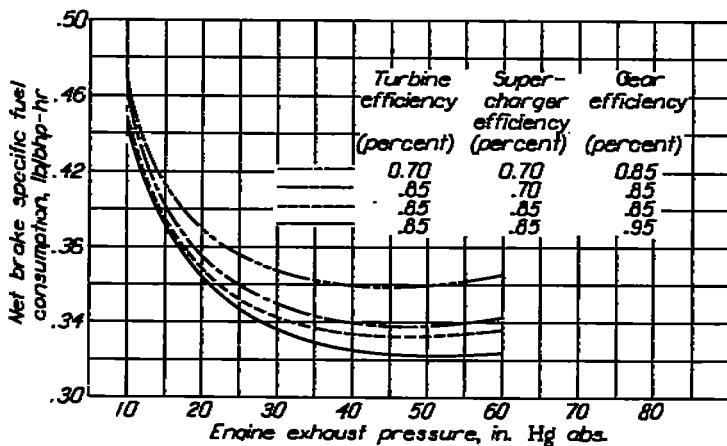


FIGURE 8.—Variation of net brake specific fuel consumption with engine exhaust pressure for various turbine and supercharger efficiencies. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; altitude, 30,000 feet; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F.

engine speed of 2000 rpm, an inlet-manifold pressure of 40 inches of mercury absolute, a fuel-air ratio of 0.063, and an altitude of 30,000 feet. The reduction in the efficiencies of turbine, supercharger, and gears causes an 11-percent increase in the minimum net brake specific fuel consumption. This percentage change in fuel consumption may be assigned to the several changes in component efficiencies as follows:

Component	Reduction in component efficiency (percent)		Increase in net brake specific fuel consumption (percent)
	From	To	
Turbine.....	85	70	6.3
Supercharger.....	85	70	1.6
Gear.....	95	85	3.1
Total.....			11.0

The reduction in fuel consumption possible if the turbine were provided with an exhaust nozzle for jet propulsion is shown in figure 9. It was assumed that the tail pipe and the

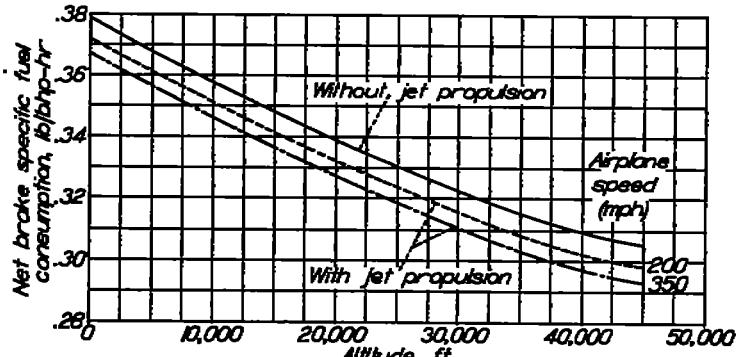


FIGURE 9.—Comparison of net brake specific fuel consumption for engine with geared turbine with and without jet propulsion at various airplane speeds and altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; turbine and supercharger efficiencies, 85 percent; gear efficiency, 95 percent.

nozzle conserve the turbine-exit velocity with negligible loss. Jet propulsion provides an additional reduction in net brake specific fuel consumption at 350 miles per hour of 3.2 percent at 10,000 feet and 3.7 percent at 30,000 feet. Calculations indicated that, for the cases of figure 9, there is little gain in decreasing the jet-nozzle area and increasing the engine exhaust pressure.

The cooling-air pressure drop required to maintain a temperature of 400° F at the rear spark-plug boss on the average cylinder and approximately 450° F on the hottest cylinder (assuming NACA standard atmosphere) at various exhaust pressures and altitudes is given in figure 10. A cross curve

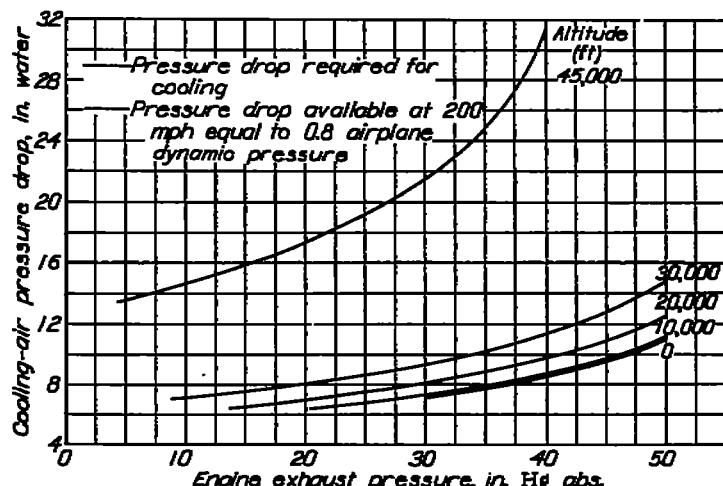


FIGURE 10.—Variation of cooling-air pressure drop with engine exhaust pressure at various altitudes. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; engine speed, 2000 rpm; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F; allowable average rear-spark-plug-boss temperature, 400° F; allowable maximum rear-spark-plug-boss temperature, 450° F; NACA standard atmosphere.

is included to show the pressure drop available at an indicated airspeed of 200 miles per hour, assuming that 80 percent of the dynamic pressure can be made available for cooling.

The curves of figure 10 indicate that operation with a high exhaust pressure increases the pressure drop required for cooling. It is possible to reduce the cooling-air pressure drop required, to lessen tendency toward knock, and to increase net power with only a small increase in specific fuel consumption by operating at an exhaust pressure below that required for minimum net brake specific fuel consumption. For example, figure 7 shows that minimum specific fuel consumption at an altitude of 30,000 feet is obtained at an exhaust pressure of 50 inches of mercury. The following table is a comparison of the specific fuel consumption, required cooling-air pressure drop, and engine power for this exhaust pressure and for an exhaust pressure of 42 inches of mercury absolute, taken from figures 7 and 10, respectively:

Engine exhaust pressure (in. Hg abs.)	Net brake specific fuel consumption (lb/bhp-hr)	Net power (hp)	Required cooling-air pressure drop (in. water)
50	0.323	1445	14.8
42	0.336	1500	11.9

The effective turbine-nozzle areas required at various engine speeds and exhaust pressures for an inlet-manifold pressure of 40 inches of mercury absolute are shown in figure 11. The areas are almost independent of altitude if supercritical flow exists through the turbine nozzles. At an engine speed of 2000 rpm and an engine exhaust pressure of 50 inches of mercury absolute, figure 11 indicates a required

manifold pressures at the same engine speed. Figure 11 indicates that the required turbine-nozzle area to hold a constant ratio of engine exhaust pressure to inlet-manifold pressure increases nearly proportionately with engine speed.

DISCUSSION OF OPERATION

The characteristics of conventional aircraft engines, superchargers, and exhaust-gas turbines are such that a given set of elements can be made to match for compound operation over only a limited range of engine and flight conditions. A full discussion of the operating problems of a compound engine that will give maximum efficiency over the entire operating range is beyond the scope of this report; nevertheless, a compromise that can be used to obtain the benefits of compound-engine operation over a range of cruising conditions will be discussed.

It is assumed that on each engine two turbosuperchargers are connected by parallel ducts with a modification that permits all the exhaust gas to be passed through only one of the turbosuperchargers and a clutch and gear train to connect that turbosupercharger to the engine crankshaft. At high engine speeds, both turbosuperchargers are free and operate in parallel. At low engine speeds, both are free but only one is required to supercharge the engine. At medium engine speeds, only one turbosupercharger is used and it is geared to the engine crankshaft and operates with a high nozzle-box pressure to provide extra power for the propeller.

For example, a system designed for geared operation with maximum economy at the following conditions is considered:

Engine speed, rpm	2000
Inlet-manifold pressure, inches mercury absolute	40
Altitude, feet	30,000

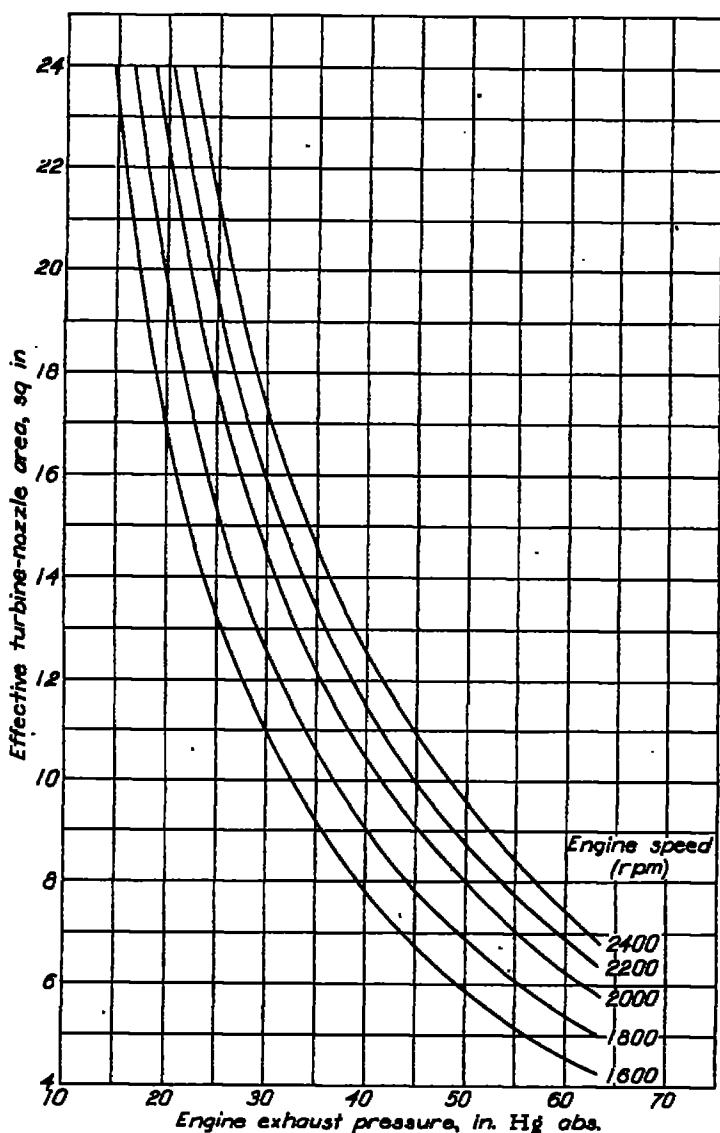


FIGURE 11.—Variation of turbine-nozzle area with engine exhaust pressure at various engine speeds. 18-cylinder radial aircraft engine with geared turbine and supercharger; fuel-air ratio, 0.063; inlet-manifold pressure, 40 inches of mercury absolute; carburetor-air temperature, 90° F.

effective turbine-nozzle area of 8 square inches. For an exhaust pressure of 42 inches of mercury absolute, the required area is 10 square inches.

It is noted in figure 4 that minimum specific fuel consumption is obtained at nearly a constant ratio of engine exhaust pressure to inlet-manifold pressure. A given turbine-nozzle area would provide a nearly constant ratio of engine exhaust pressure to inlet-manifold pressure for a given engine speed. Hence, a turbine-nozzle area chosen to give minimum specific fuel consumption at one inlet-manifold pressure would give minimum specific fuel consumption at other inlet-

manifold pressures at the same engine speed. Figure 11 indicates that the required turbine-nozzle area to hold a constant ratio of engine exhaust pressure to inlet-manifold pressure increases nearly proportionately with engine speed. At these conditions, a turbine with a closed waste gate and an effective nozzle area of 10 square inches will produce an engine exhaust pressure of 42 inches of mercury absolute and, according to figure 7, will give a net brake specific fuel consumption very close to the minimum. For expansion from 42 inches of mercury absolute to atmospheric pressure at an altitude of 30,000 feet, the theoretical turbine-nozzle discharge velocity is 3115 feet per second. For a turbine-wheel pitch-line velocity of 1200 feet per second, the corresponding blade-to-jet speed ratio is 0.385, which gives an efficiency close to the peak value for a single-stage impulse turbine. The turbine should be equipped with a gear train to provide the correct pitch-line velocity at an engine speed of 2000 rpm.

With the same engine speed and inlet-manifold pressure at lower altitudes, engine exhaust pressure remains at 42 inches of mercury absolute down to the altitude at which the pressure ratio across the turbine nozzles is subcritical and then increases to approximately 44 inches of mercury absolute at sea level. The turbine-nozzle discharge velocity is reduced to 1660 feet per second and at constant engine speed the corresponding blade-to-jet speed ratio is 0.723, giving a low turbine efficiency. Also the inlet-manifold pressure provided by the engine-stage supercharger and the geared turbosupercharger increases with a reduction in altitude, and

throttling of the superchargers is necessary. At some low altitude, the loss of turbine efficiency, the waste of supercharger power, and excessive heating of the charge would make it advantageous to declutch the turbosupercharger.

Efficient cruise operation at altitudes lower than 30,000 feet can be obtained by slightly reducing the engine speed without changing the ratio with which the turbosupercharger is geared. Little throttling of the supercharger would then be necessary, the turbine efficiency would be near its peak, and over a wide range of altitudes the engine exhaust pressure could be maintained at a high enough value to realize a substantial decrease in net brake specific fuel consumption.

At high altitudes and at engine speeds considerably lower than 2000 rpm, the geared turbosupercharger (designed for the conditions listed) operates at too low a speed and is unable to maintain the required carburetor-air pressure. At very high engine speeds (relative to 2000 rpm) at all altitudes, the turbosupercharger tip speeds exceed the safe value. For both these cases the turbosupercharger should be declutched and operated as a free turbosupercharger.

The range of satisfactory compound operation could be greatly increased by the use of a variable gear ratio between the engine and the turbosupercharger, variable turbine-nozzle area, and variable diffuser vanes to prevent supercharger surge, but these features require considerable development.

Although current equipment cannot be combined to give satisfactory compound operation over the entire range of engine speeds, the foregoing discussion indicates that reductions as great as 21 percent in the minimum brake specific fuel consumption at which the engine can cruise can be attained over a narrow range of engine speeds by the addition of a clutch between the engine and one turbosupercharger; the turbosupercharger can be connected to the engine at these speeds and disengaged at other speeds.

SUMMARY OF RESULTS

Calculations, based on test data for an 18-cylinder radial aircraft engine having a 2804-cubic-inch displacement and 40° valve overlap, gave the following results concerning operation of the engine with a geared exhaust-gas turbine and supercharger:

1. Specific fuel consumption decreased with a decrease in fuel-air ratio to a fuel-air ratio in the neighborhood of 0.063.
2. Specific fuel consumption decreased with increase in inlet-manifold pressure for a constant fuel-air ratio.
3. Minimum specific fuel consumption was obtained at the maximum inlet-manifold pressure for knock-free operation at a fuel-air ratio of about 0.063. Any appreciable increase in fuel-air ratio to avoid knock had a greater adverse effect on economy than the favorable effect of the corresponding permissible increase in inlet-manifold pressure.

4. Minimum specific fuel consumption of this combination occurred at an engine speed of 2000 rpm for the engine under consideration.

5. The net brake specific fuel consumption of the combination was a minimum for engine exhaust pressure approximately 25 percent above inlet-manifold pressure and varied only slightly from the minimum for a range of exhaust pressures from 5 to 45 percent above inlet-manifold pressure.

6. The minimum net brake specific fuel consumption of the combination at an engine speed of 2000 rpm, a fuel-air ratio of 0.063, an inlet-manifold pressure of 40 inches of mercury absolute, and with turbine and supercharger efficiencies of 85 percent was 0.323 pound per brake horsepower-hour at 30,000 feet and 0.357 pound per brake horsepower-hour at 10,000 feet.

7. A reduction in turbine and supercharger efficiencies from 85 to 70 percent and a reduction in gear efficiency from 95 to 85 percent resulted in an 11-percent increase in the minimum brake specific fuel consumption at 30,000 feet and at the same engine conditions.

8. The effective turbine-nozzle area required at an engine speed of 2000 rpm to maintain the optimum ratio of engine exhaust pressure to inlet-manifold pressure for minimum specific fuel consumption of this engine combination was approximately 8 square inches at all altitudes. The required nozzle area increased with engine speed.

9. The provision of an exhaust nozzle to conserve the turbine-exhaust velocity for jet propulsion would allow an additional reduction in fuel consumption at an airplane speed of 350 miles per hour of 3.2 percent at 10,000 feet and 3.7 percent at 30,000 feet.

10. The reduction in net brake specific fuel consumption possible with this system, as compared with the usual ungeared-turbosupercharger arrangement, was approximately 14 percent at 10,000 feet and 21 percent at 30,000 feet.

11. The engine cylinder temperature increased with increase in engine exhaust pressure. Cooling considerations may therefore necessitate the choice of an engine exhaust pressure somewhat lower than optimum, with a small sacrifice in economy.

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
CLEVELAND, OHIO, January 1, 1945.

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